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Smart Structure and Integrated System: Reinforced Nylon and Aluminum Self-Tapping Screws

ABSTRACT

Previously we reported to SAE 2002 the basic principles in materials selections for the fastening of plastics. In this current paper, we will try to increase the understanding of the automotive community regarding the usefulness and applicability of aluminum made self-tapping screws in the fastening of various thermoplastic components.

Utilization of the light alloys for the manufacturing of fasteners for plastic applications allowed us to manage efficiently the stiffness considerations, short- and long-term performance of the assembled plastic components. The results presented in this study will help designers, technologists, thermoplastic and fastener developers and fastener manufacturers, to optimize mechanical performance of assembled automotive components, where self-tapping screws will be used.

INTRODUCTION

Historically, from the dawn of humankind to the present time, all techniques for joining has been very pragmatic, concerned with needs and results rather than with the strong ideas and theories [1]. There are various design strategies associated with plastic part assembly for the automotive and transportation applications. The assembly methods that are utilized must establish mechanical unity between joined various parts that make up the functional and durable end-use product [1-27].

Performance of assembled plastic components strongly depends on the design, processing technology, the mechanical and physical properties of materials of all joined components at bulk and local (including various engagement and contact) areas, and utilized joining technology. The selection of the right material(s) for the design is an essential step in this combined process [1-12]. By understanding the following two correlation between design and mechanical performance of used materials, loading conditions, influence time-temperature and various environment effects. It is possible to optimize design and material(s) selection, and assembly parameters (such as clamp torque and clamp stress, number of fasteners, etc.).

Today the range of materials and properties available to a mechanical engineer is much larger and growing rapidly. On a practical level, the design engineer has always-ready access to information on 50 to 1,500 (or more) materials depending on the range of different automotive applications. Conceptual aspects of the design of thermoplastic parts for assembly and manufacturing were discussed in [3-13, 16-20, 22-29].

Figure 1. An example of the assembly (fastening technology) of the plastic part and metallic component.

There are varieties of modern technological ways of the 21st century to join plastic made parts into assembled products. The oldest of these ways is mechanical joining using integral attachment or fastening. The self-tapping screws were developed over 60 years ago, and they are still widely used for thermoplastic parts assembly in various industrial applications due to efficient technical and economical features. Assembling with the self-tapping screws is the very fastest and at least expensive process in terms of total cost. With so many technological and commercial options available for the various fasteners, the accurate selection of fasteners type is required to update previous experience in material(s) selection, design and assembly technology [1-20, 29-31]. In this current report, we are presenting new trends and imagined directions for key joining processes, which focused on the utilization of the light alloys for manufacturing of self-tapping fasteners for thermoplastics applications. Proposed fastener(s) material replacement (from steel to aluminum) will allow managing the stiffness considerations, short- and long-term performance of the assembled parts for various automotive applications (Figure 1).

ADVANCED CONSIDERATIONS OF THE DESIGN-MATERIAL-PERFORMANCE-ECONOMIC

ADVANTAGES AND LIMITATIONS OF FASTENERS

Thread forming screws (Figure 2) are very typical for various materials applications (metallic and non-metallic, including thermoplastics).

Figure 2. An example of metallic self-tapping screws.

The type of thread forming screws most commonly used for plastics are: - self-tapping; - self-cutting. These self-tapping screws offer advantages unachievable by adhesives and welding. For example, they offer the capacity to be disassembled for maintenance or recycling. Mechanical performance of the joint strongly depends from all basic design considerations including basic geometry of joined parts, local geometry at thread engagement areas, loading conditions, and used materials. The focus of the basic considerations is oriented on the influence of the design, manufacturing and assembly practices on cost, weight and efficiency of fastening of thermoplastics in various automotive and transportation applications.

The following reasons will present the basic advantages of self-tapping fasteners:

- Design freedom (ability to join similar and dissimilar materials such as plastics, various steels and light alloys: aluminum, titanium and magnesium based).
- Universal in rotation direction (both types of self-thread forming (or self-cutting) are available: right-forming and left-forming). Assembly automation.
- High level of standardization (screw types, shape and profile, etc.) and worldwide availability.
- Visibility for disassembly and joint reopenability and reusability (second use) of fasteners.
- Low cost, non-high technology requirements to operators and various/adjustable volume capability.

The following reasons will present some limitations of self-tapping fasteners:

- Stiffness considerations related to differentials in the mechanical and physical (coefficients of linear thermal expansion, density) properties of materials (joined parts and used self-tapping screws).
- Life considerations related to differentials in the mechanical of joined materials.
- Effects of clamp stress relaxation (related to creep, temperature, moisture) and loosening of fasteners.
- Design limitation (stress concentration, notch sensitivity, length of engagement at thread area, contact stresses under head of screw).
- Number of used fasteners.
- Cost of disassembly for maintenance or disposal.
- Esthetics/appearance
  - Needs to have an access from one side
  - Visible from fine surfaces side
  - Corrosion of visible damaged surfaces
  - Corrosion at engagement areas

ECONOMIC OF SELF-TAPPING SCREWS

Economics is playing a very important role in plastic parts design, manufacturing and assembly. Typically, the labor involved in producing individual automotive components – operations such as cutting, forming, and machining (for metal based parts) or plastics molding and finishing – represents between 8-30% of total manufacturing cost. The labor involved in inspection and testing typically represents 4-15%. The labor included with assembly can run between 50-75% of total manufacturing cost [4, 19].

Figure 3. Housing of two shells (shelves) pump.

Depending on the type of fastening selected and the method of assembly, the installation cost may represent a four times multiple of the fastening purchasing cost. In general, the total cost for a fastening may be made up of 20% fastener purchasing cost plus 80% fasteners assembly cost. The purchasing cost represents the fastener it. Self-tapping screws are very efficient in various applications where it exists or doesn't exist to have pre-formed (or drilled) hole. Below we will discus the efficiency of design and assembly technology options for multi-shells injection molded pumps housing (Figure 3) from aspects of life-cycle engineering. As an alternative to self-tapping screws, solid and blind rivets may be laid out the advantages and drawbacks of each design approach (Table 1).

Table 1. Efficiency of various assembly technologies.

Performance with Type of Fasteners	Self-tap. Screws	Solid Rivets	Blind Rivets
Degree of Reusability	High	Very L.	Low
Stress/Size Ratio	High	Low	Low
Purchasing Cost	Low	Low	High
Cost of Assembly	Low	High	High
Cost of Disassembly	Low	Very L.	High
Level of Automation	High	Low	Low

For conditions of continuous (life-cycle) use of a pump, the blind rivets will satisfy economical requirements to assembly cost. The specifics of this design application, related to field servicing require disassembling a pump at some point after the useful service life is expended. The factor of reusability should be the first priority parameter in this evaluation of the assembly for fastener selection. Self-tapping screws could be used to eliminate an internal threaded operation. In planning any fastened assembly, the following two points can be of great help in achieving manufacturing joints which are efficient: 1) Joints whose strength approaches the exceeded strength of the component materials. 2) Joints, which require only reasonable, amount (number) of fastener and cost of installation. First, consider the joint mechanics of how the candidate fastening will apply clamping pressure with the influence of time-temperature conditions. Comprehensive test programs at various end-use mechanical and environment condition follows after these considerations.

PRINCIPLES IN MATERIALS SELECTION FOR FASTENING OF PLASTICS

Material Properties Needed for Design for Assembly

The selection of right material(s), for assembled plastic parts, is an important process in the designing and manufacturing process for automotive applications [11, 16-20]. Incorrectly selected material can lead to possible damages or failure of an assembly and significantly decrease performance [6, 9, 23-27, 28-31]. Later we will discuss the basics of the mechanics of fastening and the design-materials considerations, which will help us with the right material selections for self-tapping screws. These considerations related to the differentials in the mechanical (deformation), physical (coefficients of linear thermal expansion, density, etc.) properties of materials (joined parts and used self-tapping screws). Many interesting technical results were published on the mechanics of fastening of plastics [18-29]. Previously developed concepts of self-thread forming metallic assemblies [3-8, 12, 30] were transferred to plastics and composites applications. Various steels were used as materials of the first approach for self-tapping screws for the assembly of thermoplastics. This approach was successfully utilized in many industrial applications. Some limitations of thermoplastic assemblies, where steel made self-tapping fasteners were used, are related to the kinetic of clamp-stress relaxation and may create leakage of fluids or gases from various hollow parts during long-term non-isothermal service conditions.

Table 2. Short-term mechanical properties of materials needed for fastened thermoplastic parts design, design analysis & optimization.

Mechanical Properties	Plastic	Screw
Tensile (T°, RH%)[1]		
Stress-strain curve	+	+
Strength at yield		
Strength and strains at break		
Tensile modulus and Poisson's rat.		
Compressive (T°, RH%)		
Stress-strain curve	+	-
Strength		
Young modulus at compression		
Shear (at 23°C only)		
Shear Strength	+	+
Shear modulus		
Flexural (at 23°C only)		
Strength at break	+	-
Strain at break		
Resistance to Impact (T°, RH%)		
Un-notched	+	-
Notched		+
Transition temperature		
Fracture Mechanics		
Fracture toughness (K_{IC} K_{IIC} , etc.)	+	+
Tribological - Friction (T°, RH%)		
Static coefficients of friction	+	+
Dynamic coefficients of friction		
Hardness	+	+

The selection of materials for assembled thermoplastic parts must be closely coupled with the influence of various end-use and environmental conditions. An accurate plastic part design for assembly requires familiarity with a broader range of materials properties. Physical and mechanical properties of utilized materials needed to be conducted at various end-use environmental and mechanical loading conditions typically for under-the-hood applications. The following two base mechanical properties are very important for the design of assembly of plastic parts: 1) Short-term properties (static and dynamic). 2) Long-term properties (fatigue, creep, stress relaxation[2]). Short-term mechanical performance of thermoplastic and metallic fasteners is important for quality control at design and

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[1] (T°, RH%) – with the influence of temperature and moisture effects.

[2] Some technical problems are in development of the stress relaxation data (ASTM standard for stress relaxation of plastics was discontinued).

manufacturing stages, which allow to ensure the constant properties of used materials and processing and assembly technologies.

Table 3. Long-term properties needed for fastened parts design, design analysis & optimization

Mechanical Properties	Plastic	Screw
Tensile (T°, RH%)		
Creep modulus	+	+
Creep rupture strength		
Creep curves		
Isochronous creep curves		
Ten.-ten.fatigue curve (*S-N*)		
Fatigue crack propagation		
Stress/notch factors data		
Compressive (T°, RH%)		
Stress relaxation	+	+
Flexural (to substitute tensile)		
Creep modulus	+	-
Creep rupture strength		
Creep curves		
Flexural fatigue curve (*S-N*)		
Influence of environment, etc.		
Corrosion and degradation	+	+
Stress corrosion		
UV resistance		–
Biological stability		
Friction (T°, time, environment)		
Static coefficients of friction	+	+
Dynamic coefficients of friction		

Table 2 provides listing of short-term properties needed for plastic parts design for assembly with self-tapping screws. Table 3 provides long-term properties of used thermoplastic and metallic screws, which are very important in predicting of the service time of fastened plastic components.

For design for assembly, materials pre-selection, manufacturing and joining process optimization, we need to obtain and take into account the following properties:

- Physical (material density (ρ), melt point (T_m) and glass-transition (T_g) temperatures, and viscosity).
- Thermal (conductivity, coefficient of linear thermal expansion (α), fire resistance)
- Manufacturing (heat treatability, hardenability, machinability, shear rate, temperature range, etc.).

<u>Basic Criterion in Material Selection for Integrated System: Smart Solutions in Fastening of Thermoplastics.</u>

The material properties of joined parts (fastener and thermoplastics) may limit mechanical performance of the assembly of plastic components (Figures 1, 3-4).

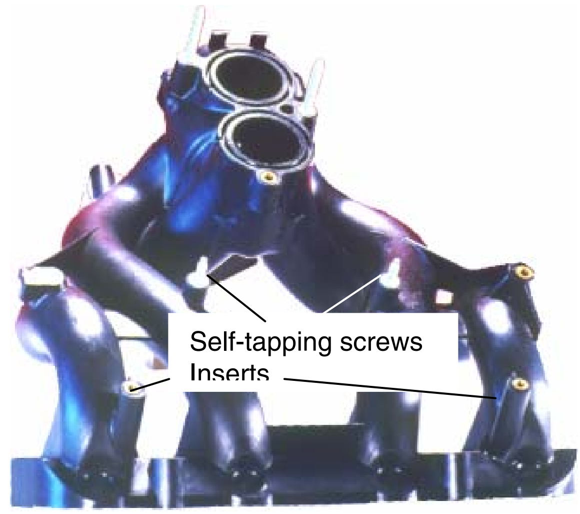

Figure 4. Combined fastening of thermoplastic components (using self-tapping screws and inserts).

Traditionally [3-13] the combination of several properties such as ultimate strength, elongation to failure, modulus of elasticity, density, and coefficient of linear thermal expansion, etc. was taken into account in the design of various assembled parts. In the current study, we will analyze the combined influence of the following five important parameters on the mechanical performance of thermoplastic-metal assemblies:

1) density (specific weight) - ρ;
2) coefficient of linear thermal expansion - α ;
3) elastic (Young) modulus - E ;
4) tensile strength - σ_u ;
5) fracture toughness – K_{1C} (Mode I, or mixed Modes with various ratio of K_I / K_{II} , etc.).

Tribological properties are very important for the optimization of joining parameters such as: driving torque, tightening torque). Mechanical performance data may be presented in the following two ways: 1) using graphs (Figure 5, the tensile stress-strain curves for various metals used for manufacturing of fasteners); 2) numerical format (Table 4, the tensile strength of fiber-glass reinforced nylon 6). This format is very convenient for the material pre-selection stage. The envelope data is more informative (Figure 6 and Figure 9), when several basic properties are evaluated together.

In selecting materials for the design of thermoplastic parts for assembly (various automotive under-the-hood application), we need to take into account the following material requirements:

- Low specific gravity (density) ρ of used materials (metallic and thermoplastic based) with balance of normalized strength (σ / E).

- Balance of stiffness (E - Young modulus) and fracture toughness (K_{1C}).
- High resistance to time temperature-effects.
- High resistance to cycling loading.
- Sufficient corrosion resistance to various automotive fluids, chemicals and environmental effects.

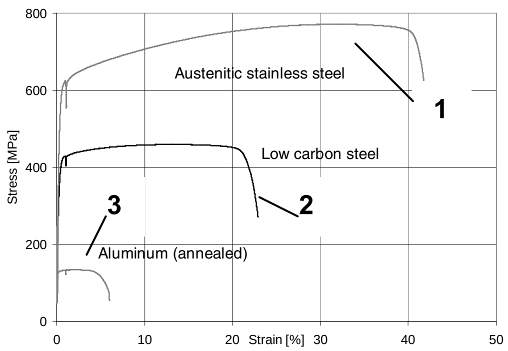

Figure 5. Tensile stress-strain curves for two grades of steels (1-2) and aluminum (3) for fasteners applications.

Table 4. Efficiency of Short Fiber-Glass Reinforcement on Mechanical Performance of Molded Nylon 6

GF wt. %	ρ g/cm^3	Strength σ_u, MPa	Young Modulus E, GPa	Efficiency of Reinforcement $k_{gf} = \sigma_{pl}/\sigma_m$
0	1.13	82	2.8	1.00
6	1.16	85	4.0	1.04
14	1.23	125	5.8	1.52
25	1.32	160	7.3	1.95
33	1.38	200	9.1	2.43
45	1.49	218	11.8	2.65
50	1.56	262	17.2	3.19
63	1.74	281	23.2	3.42

Table 5. Efficiency in metallic part design by stiffness to weight criteria (normalized to aluminum[3])

Material	$\sqrt[3]{E}/\rho$	E/ρ	E_i/E_{AL}	ρ_i/ρ_{AL}
Aluminum	1.00	1.00	1.00	1.00
Steel	0.50	1.02	3.00	2.88
Titanium	0.71	1.01	1.36	1.74

- Sufficient strength of knit-lines
- Continues use temperature up to 125-150°C
- Short-term peak temperature up to 170°C

Density (ρ), normalized stiffness (E/ρ), normalized strength (σ/E), coefficient of linear thermal expansion (α), and fracture toughness[4] (K_{1C}) are very important parameters in designing for assembly. The details on these basic parameters of various materials are shown in Tables 4- 6.

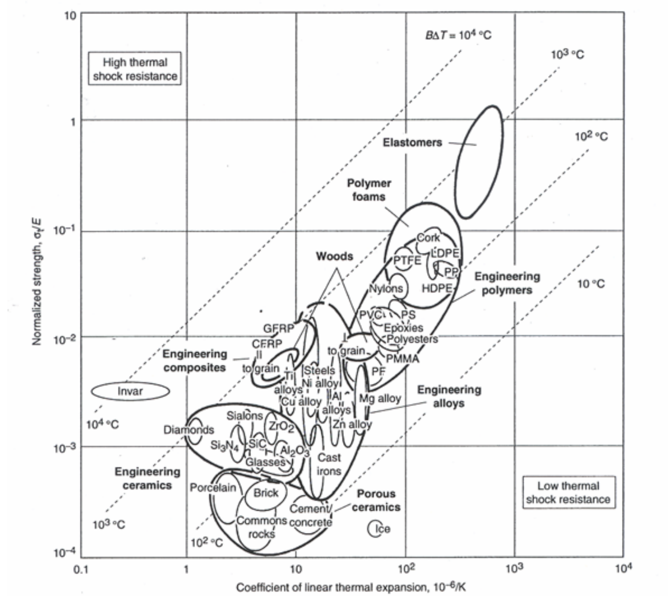

Figure 6. Relations between the linear thermal expansion (α) and normalized strength (σ/E).

Utilization of Traditional Mechanical Performance Parameters in Material(s) Selection

Efficiency of utilization of lightweight material in plastic parts design for assembly may be evaluated by the following comprising between material modulus E and density ρ for the flexural loading conditions. The designed part has round shape with diameter d and length l. The stiffness of the screws made from various materials should be the same:

$$E_1 J_1 = E_2 J_2; and \frac{\pi d_1^3}{6} E_1 = \frac{\pi d_2^3}{6} E_2 \quad (1)$$

Considering above presented conditions

$$\frac{d_1^3}{d_2^3} = \frac{E_2}{E_1}; \text{ and that } l_1 = l_2 = l. \quad (2)$$

The weights of the screws are:

$$w_1 = \rho_1 \frac{\pi d_1^2}{4} l_1, \text{ and } w_2 = \rho_2 \frac{\pi d_2^2}{4} l_2; \quad (3)$$

The ratio of the weights is equal to:

[3] For aluminum alloy with Young modulus E = 70 GPa and density ρ = 2.7 g/cm^3 (see Table 7).

[4] Some principles of the application of fracture mechanics in design of various fasteners were discussed in [14-15].

$$\frac{w_1}{w_2} = \frac{\rho_1 d_1^2}{\rho_2 d_2^2}; \ \frac{w_1}{w_2} = \frac{\rho_1 E_2^{2/3}}{\rho_2 E_1^{2/3}}. \quad (4)$$

Unconstrained plastic (or metallic) part respond to temperature increases by expanding and to temperature decreases by contracting. Tables 6-7 Illustrate that different materials may have widely different coefficients of linear thermal expansion (α), Young modulus (E) and tensile strength (σ). Thermoplastics typically have α that are considerably higher that those of other materials, such as various metals. As the Tables 6-7 show, this difference may amount to a factor of 15. Presented data on α and relation between thermal properties and normalized strength (σ / E) of various materials allow to predict induced thermal stress σ_t at a temperature change ΔT for a constrained, initially unstressed plastic component (one material only):

$$\sigma_c = \frac{E\alpha\Delta T}{C} \quad (5)$$

Where:
E - Young modulus
ΔT - Temperature change
α - Coefficient of linear thermal expansion
C - Coefficient of constraint conditions. The coefficient of constraint C is equal to:

$C = 1$, for a axial constraint ($\varepsilon_y = 0; \varepsilon_z = 0$); (6)

$C = (1-\mu)$, for bi-axial constraint ($\varepsilon_z = 0$); (7)

$C = (1-2\mu)$, for tri-axial constraint (8)

μ = Poisson's ratio.

For thermal loading conditions, the aluminum made screws are more compatible with several fiber-glass reinforced polyamides, PBT and PET based plastics (Table 6 and Figure 6). Linear thermal expansion of un-filled plastics is significantly higher of aluminum and steel. Presented in [14] analysis shows that the precise level of stress in the plastics and composites depends on the relative compliance of the component to which it is attached and on assembly stress (Figure 8). Considering kinetics in the reduction of tightening loads (Q_{VO}) during mechanical and thermal loading, the applied to plastic load is equal to:

$$Q_{PL} = Q_{VO} - F\frac{\lambda_{SC}}{(\lambda_{SC} + \lambda_{PL})} + \Delta Q_{TEM} \quad (9)$$

Where:
ΔQ_{TEMP} = Induced load from temperature change ΔT.

Table 6. Basic physical (density - ρ), mechanical (Young modulus - E) and thermal (coefficient of linear thermal expansion - α) properties of various materials

Material	α **=10^{-6}/°C**	ρ **=g/cm^3**	E **= GPa**
Metal based			
Steel	10.8-11.3	7.8-8.0	210
Aluminum	19-#	2.70-2.77	70
Brass	17-21	8.90	140
Magnesium	23-25	1.75-1.81	45
Titanium	95	4.7	45
Un-filled plastics			
ABS	110-170	1.16-1.21	0.9-2.9
Nylon 6	144	1.12-1.14	2.6-3.2
Nylon 66	144	1.13-1.15	2.4-3.2
PC	122	1.20	2.30
PBT	135	1.34	2.0-3.1
PP	145-180	0.90-0.91	1.14-1.55
Reinforced plastics			
ABS	36	1.18-1.36	0.5-6.9
Nylon 6	12-38	1.22-1.63	5.5-15.6
Nylon 66	12-32	1.22-1.51	4.8-11.0
PC	40-32	1.25-1.63	2.62
PBT	14-29	1.43-1.66	3.05
PET	22-32	1.39-1.80	9.0-12.4
PP	48-58	1.14-1.21	4.8-10.4
SMC	12-17	1.80-2.15	10-19.1
Graphite	-0.36	1.60-1.70	145
Mineral filled			
Nylon 6	36-54	1.22-1.60	4.2-4.3
Nylon 66	32-53	1.20-1.63	4.1-44
Reinforcements			
Glass	5.1-8.2	2.19-2.5	68-86
Carbon	6.0	1.75-2.15	220-650

$$\Delta Q_{TEMP} = \frac{l\Delta T(\alpha_{PL} - \alpha_{SC})}{(\lambda_{SC} + \lambda_{PL})} \quad (10)$$

λ_{SC} and λ_{PL} = Coefficients of compliance of the components of self-tapping joint.

$$\lambda_{SC} = \frac{l_{SC}}{E_{SC}A_{SC}}; \text{ and } \lambda_{PL} = \frac{l_{PL}}{E_{SC}A_{PL}}; \quad (11)$$

α_{SC} and α_{PL} = Coefficients of linear thermal expansion of joined materials/components (screw and plastic part). Coefficient of linear thermal expansion of metallic screw is lower then the joined thermoplastic ($\alpha_{SC} \leq \alpha_{PL}$). An external load factor χ_{PL} is equal to:

$$\chi_{PL} = \frac{\lambda_{SC}}{\lambda_{SC} + \lambda_{PL}} = \frac{[l_{SC}/(E_{SC}A_{SC})]}{[l_{SC}/(E_{SC}A_{SC})] + [l_{PL}/(E_{PL}A_{PL})]}$$

(12)

The nominal stress acting at plastic component may be defined as follows:

$$\sigma_{PL} = Q_{PL} / A_{PL} \quad (13)$$

Where: A_{PL} = Cross section area of plastic.

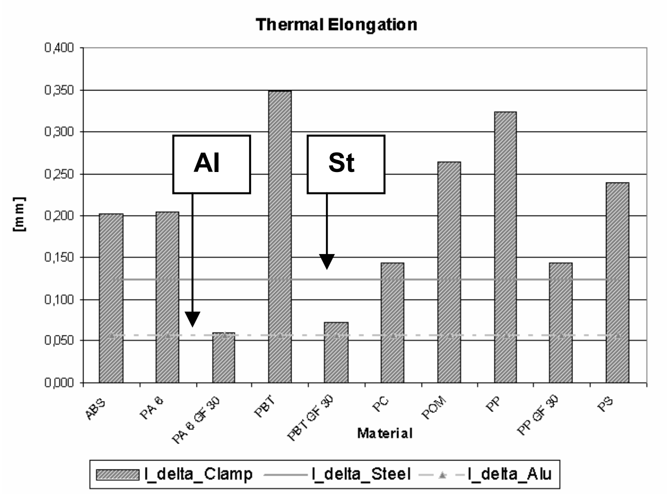

Figure 7. Relations between the linear thermal expansion α of various thermoplastics and thermal elongation of self-tapping screws (aluminum - **Al** and steel - **St** made) for unconstrained conditions.

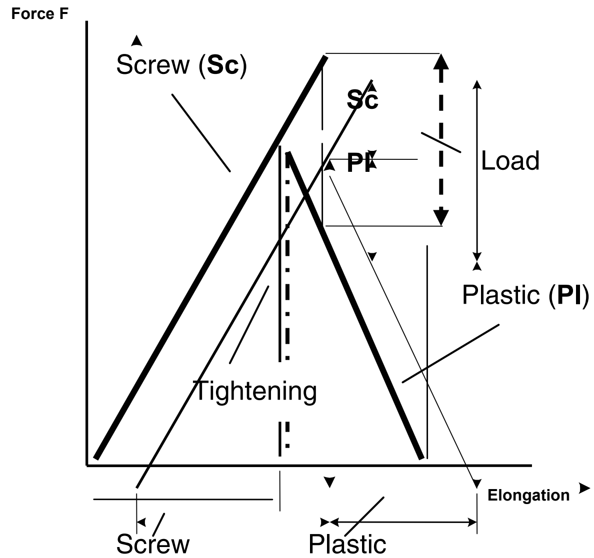

Figure 8. Loading diagram for a plastic-screw joint

Value of induced thermal stress σ_t depends on ratio of $\alpha_{PL} / \alpha_{ST}$. Typically $\alpha_{PL} \succ \alpha_{SC}$ (see Table 7-8). It is possible to minimize the stresses induced by differential thermal expansion (or contraction) and differential deformation properties (Young modulus) by the following three ways: 1) *minimize* the difference ($\Delta \alpha$) in the coefficients of linear thermal expansion between the materials comprising the structure/joint (metallic screw and thermoplastic). 2) *minimize* the temperature differences (ΔT) the structure will experience during end-use, assembly and shipping/storage. 3) *optimize* ratio of the coefficients of compliance λ (11), which strongly depend on deformation properties (Young modulus E) of the materials comprising the joint.

Table 7. Efficiency of light alloys (aluminum based) for fastening of thermoplastics

Parameter	**Un-filled**	**Reinforced**	**Thermosets**
Normalized to steel (ST)			
α_i / α_{ST}	13	3	≈ 0
E_i / E_{ST}	0.0143	0.0476	0.690
Normalized to aluminum (AL)			
α_i / α_{AL}	7.580	1.2105	≈ 0
E_i / E_{AL}	0.0429	0.1428	2.071

Analysis of the basic physical, mechanical and thermal properties of various metals used for fasteners is showing that (Table 6-7):

- Coefficient of thermal expansion for aluminum (α_{AL}) is approximately twice higher than for steel (α_{ST}) and its value is very close to (α_{PL}).
- Modulus of elasticity (Young modulus E) of aluminum (E_{AL}) is three times less than steel (E_{ST}).
- Density of aluminum alloys (ρ_{AL}) is three times less than for steels (ρ_{ST}).
- Aluminum made fasteners should show some advantages in performance with the fiber-glass reinforced nylon for automotive applications at non-isochronous thermal and various loading conditions.

<u>The Application of Linear Fracture Mechanics (LFM) Criterion to Material Selection</u>

The ability of the methods of Linear Fracture Mechanics (LFM) to separate initiation toughness and crack propagation resistance gives the designers additional precision tool and more flexibility in preventing fracture of assembled plastic components and used fasteners [14-15, 31-32].

Fracture toughness at damaged thread area of metallic screws may be calculated by equations (14)-(15). The Mode I of stress intensity factor:

$$K_1 = \int_0^a \sigma(x) m_1(x,a) dx \qquad (14)$$

$$K_{II} = \int_0^a \tau(x) m_{II}(x,a) dx \qquad (15)$$

Where:

$\sigma(x)$, $\tau(x)$ are correspondingly normal and shear stresses distribution acting perpendicularly or at potential crack plane.

$m_I(x,a)$ and $m_{II}(x,a)$ are the appropriate weight functions of the damaged (cracked) thread and a unique property of screw geometry. Weight functions $m_I(x,a)$ and $m_{II}(x,a)$ can be determined by finite element analysis (FEA) or analytically. Accurate Mode I and Mode II weight functions are available in the literature [32].

Some details related to fracture toughness (K_{1C}) of nylon were discussed in [33-34]. It is very important to satisfy plane strain conditions in development of correct fracture toughness (K_{1C}) data for injection molded parts, when the thickness of walls may vary. The minimum thickness of the specimens (walls) needed to satisfy plane strain conditions maybe calculated by the following equation:

$$t_{\min} \geq 2.5\left(\frac{K_Q}{\sigma_y}\right)^2 \qquad (16)$$

Where:

K_Q - is provisional (assumed) value of stress intensity factor, but whose validity is not yet established.

σ_y - tensile strength at yield.

For nylon based plastics with fiber-glass reinforcement above 25 wt.%, the minimum needed thickness $t_{\min}$ is 2.8 mm (which is correct for available for the tests plaques with the thickness 3.2 mm or 4.0 mm). Figure 9 presents fundamental relations between one of the basic mechanical parameter of material performance - tensile strength (σ_u) and fracture toughness (K_{1C}). Detailed data on fracture toughness (K_{1C}) for various nylons, steel and aluminum is discussed in Table 8. By fracture toughness (K_{1C}), aluminum is close to thermoplastics than steels also (Table 8). Areas of attachments, such as bosses are very anisotropic by mechanical properties due to fiber-glass orientation. Table 9 presents data on the influence of fiber-glass orientation on normalized[5] fracture toughness of nylon [34]. Similar difference in resistance to fracture between nylon 6 and nylon 66 maybe demonstrated using impact data also. Plastic flow orientation at fastening areas (bosses) depends on the design of an injection-molded part and molding tool. Front of the flow has curvilinear shape, which influence on the fiber-glass orientation and two-dimensional fracture modes (K_I / K_{II}) as well.

[5] Normalized to the value of fracture toughness K_{1C} (at flow direction).

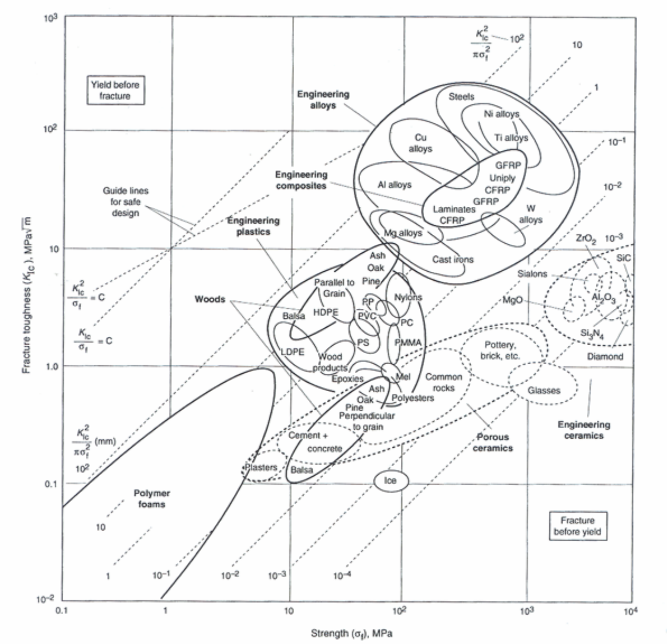

Figure 9. Relations between material tensile strength (σ_u) and fracture toughness (K_{1C}).

Table 8. Fracture toughness (MPa x m$^{1/2}$) of various structural materials used for fastening.

Material	**Fracture toughness (K_{1C})**	
Material state	*Dry as Molded*	*50% RH*
Steel	30-50	-
Aluminum alloys	20-40	-
Nylon 6 (un-filled)	5.0	8.2
Nylon 6 (reinforced)	12	-
Nylon 66 (un-filled)	4.0	7.0
Nylon 66 (reinforced)	10	-
PC (un-filled)	2.2	-

Table 9. Consideration of fiber-glass and crack orientation on normalized fracture toughness of nylon (33% short glass-fiber reinforced, 23°C, Dry-as Molded)

Crack orientation	**Flow Direct.**	**Across Flow**	**By angle 45°**
Fracture toughness	1.00	0.600	0.776

Presented in Table 9, the results show a strong dependence of the of the value of fracture toughness with fiber-glass and crack (or knit line) orientation for nylon based plastics. The ratio of $K_{1C(ACROSS)}$ to $K_{1C(FLOW)}$ is approximately 0.6 and this ratio may change in thickness of molded part. Interaction of orientation of fiber-glass and crack may create mixed Modes conditions (K_I / K_{II}).

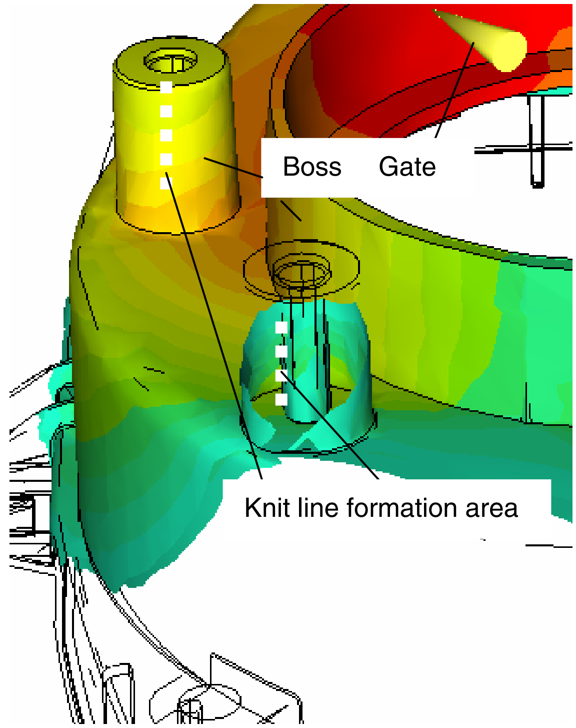

Figure 10. Plastic flow patterns in boss area with knit-line formation (MoldFlow® data).

CONSIDERATION OF MECHANICAL PERFORMANCE OF NYLON/POLYAMIDE AND ALUMINUM

REINFORCED NYLON/POLYAMIDE – MATERIAL OF CHOICE FOR AUTOMOTIVE APPLICATIONS

Nylons (polyamides) are high performance semi-crystalline thermoplastics with a number of attractive physical and mechanical properties. The following four important interrelations *thermoplastic – molding tool – plastic part-assembly technology* must be considered at the outset by those specifying polyamide (nylon): nylon 6 is a family of related plastics, not a just a single composition. Reinforced nylon plastics (with 15 – 40 wt.% fiber-glass reinforcements - GF)[6] are commonly used in design of various assembled parts]. Fiber-glass reinforced and mineral filled nylon plastics (25 – 45 wt.% GF/MF) are used in automotive and transportation design also. Typically the weight of glass-fiber reinforced nylon-based automotive part is 40-55% less than a similar design made from stamped steel.

This family of fiber-glass reinforced or reinforced and filled plastics can be considered that all compositions have the following injection molding advantages for various assembled automotive parts [35-38]:

- Fast overall processing cycles and ejectability (part release from molding tool) is very good

[6] wt.% - level of reinforcement or filled by weight.

- Good mechanical performances of molded parts after several re-molding/re-grind cycles (mechanical property losses are minimal, etc.)
- Moldability to close tolerances.
- Predictable mold and annealing shrinkage; small tendency for warpage
- High flow and toughness in thin sections, easy to fill of complicated shapes of attachments areas
- Sufficient knit (weld) line strength (including bosses) for resistance to hoop stresses

Short-Term Mechanical Properties of Nylon 6

Comprehensive tensile properties of non-reinforced and fiber-glass reinforced plastic should include the following key strength and deformation parameters needed for an analytical and FEA (Young modulus - E, Poisson's ratio - μ, tensile strength at break - σ_{TEN}, ultimate elongation at break - ε_u). Short-term tensile properties for four grades of nylon 6 based plastics are shown in Table 10.

Table 10. Typical Properties of Capron®[7] Nylon 6 Based Plastics (all HS – Heat Resistance Package) at Room Temperature (23°C, Dry-as Molded, DAM)

Mechanical Properties	**8202 HS**	**8231G HS**	**8233G HS**	**8235G HS**
Fiber-glass content, wt.%	0	15	33	50
Density - ρ, gm/ cm^3	1.13	1.23	1.38	1.56
CLTE, α =10^{-6}/°C	100	39	21	14
Poison's Ratio, μ	0.35	0.35	0.35	0.35
Tensile Str. - σ_{TEN}, MPa	82	125	200	262
Young Modulus (E), GPa	2.85	5.96	9.18	17.2
Ultimate Elong., ε_u %	70	3.5	3.0	2.72
Flexural Str. - σ_{FLEX}, MPa	112	180	270	295
Notched Izod Impact, J/m	55	60	115	125

The influence of such factors as time, temperature, moisture, plastic composition (additives, fillers and reinforcements), molecular orientation, and crystallinity distribution are very important for the performance of injection molded parts [6, 11, 35-40]. Because all nylons are moisture sensitive thermoplastics, this short-term data should present mechanical performance of the standard specimens and molded parts at various level of moisture in typical for manufacturing and end-use. Under room temperature and 50% RH, nylon 6 could eventually absorb 2.75-2.8 wt.% water (Table 11).

Table 11. Influence of Relative Humidity on Water Absorption (in %) in Non-Filled Nylons (at 23°C in air)

Nylon	**30% RH**	**50% RH**	**62% RH**	**100% RH**
Nylon 6	1.1	2.75	3.85	9.5
Nylon 66	1.0	2.5	3.6	8.5

Everyone wt.% moisture increase in nylon may result in 0.2 to 0.3% increase in dimension. The relationship between absorbed moisture in injection molded parts or specimens and time of exposure is different for different thickness of nylon made parts (Figure 11).

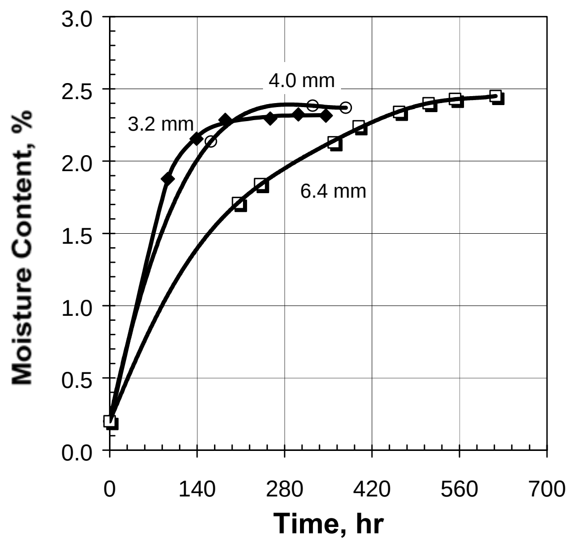

Figure 11. Moisture absorption (in wt.%) vs. time for 33 wt.% glass fiber reinforced nylon 6 with various walls thickness (mm): 3.2; 4.0: 6.25.

Under dry-as-molded conditions (DAM), nylon usually contains 0.1-0.3 wt.% water[8]. By controlling moisture content in that range, it is possible to reduce brittle failure of the molded parts. After a bag or container with the pellets has been open and plastic exposed to the air, the nylon pellets starts picking up moisture. Initially dry (0.1-0.3 wt.%) nylon at room temperature conditions (23°C) and 50% RH will raise the moisture level by 0.3 wt.% in 4 hours and 0.45 wt. % in 8 hours. For winter conditions (when it is cold and dry, 25% RH), the time required to pick up 0.45 wt.% moisture would be about 50 hours. As a rule, ISO 1110 procedures (62±1 %RH at 70°C) were utilized in this study for conditioning of the

[7] Capron® - is the registered trademark of BASF International for its nylon based plastic products

[8] ASTM D-4066 specified for nylon 6 moisture content "as received", before the package is opened and the material exposed to the outside air, equal 0.2 wt.%.

molded various automotive components and test specimens. Figure 12 shows changes in tensile strength at wide range of moisture and temperature effects.

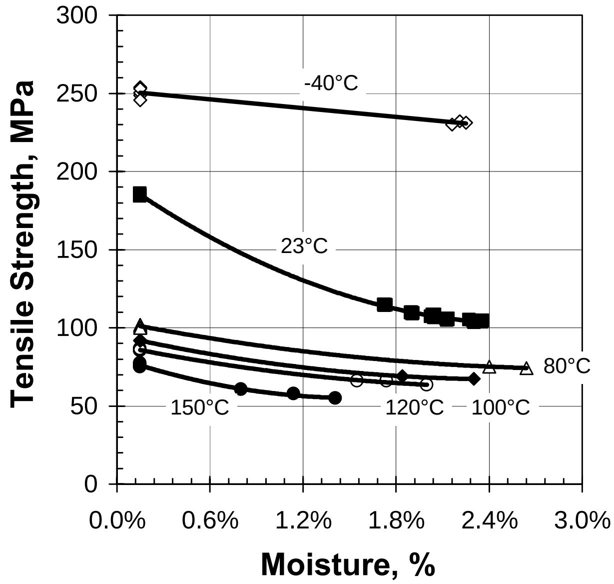

Figure 12. Influence of end-use temperature and moisture on the tensile strength of reinforced nylon 6 (33% short glass-fiber).

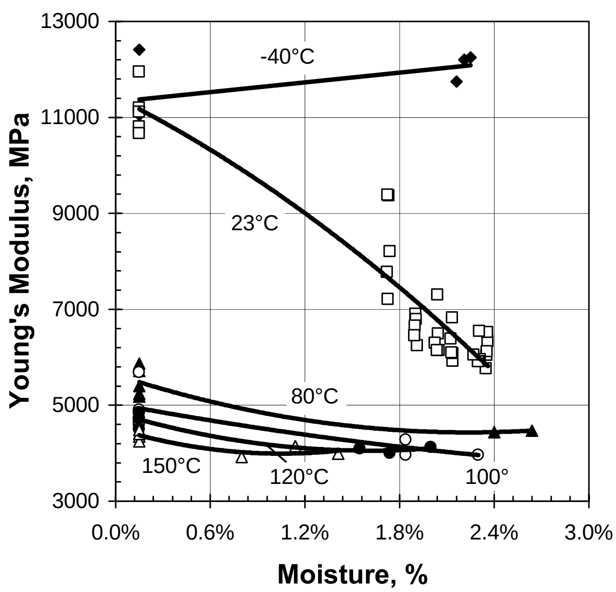

Figure 13. Influence of temperature and moisture on Young's modulus (nylon 6, 33% short glass-fiber).

At –40°C, tensile strength was changed very slightly (decreases by 10% approximately). The significant changes were observed at room temperature (23°C): the tensile strength decreases by 45%. At elevated temperatures (from 80 to 150°C), tensile strength decreased by 20% approximately. In nylons, absorbed water exist in the amorphous phase yet its presence could influence both crystallization and crystalline phases. With water absorption, γ phase is transformed to the more stable α phase. Absorbed water behaves as a plastcizer that decreases glass transition temperature (T_g), which lowers tensile strength and Young's Modulus (E). Moisture and temperature have similar effects on the tensile properties of nylon. Effects of moisture on tensile strength and Young's modulus are shown in Figures 13 and 14.

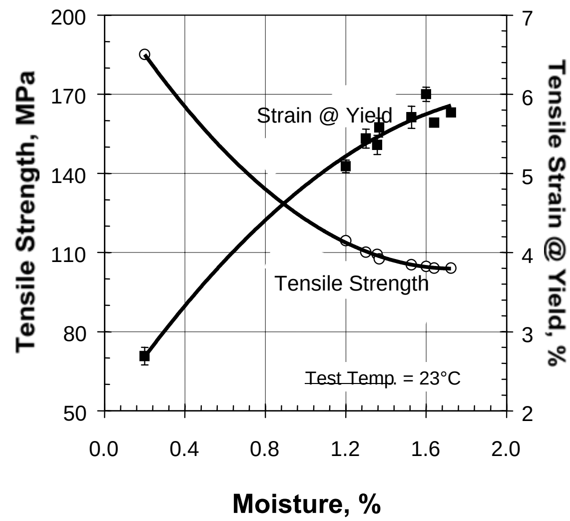

Figure 14. The effect of moisture on tensile properties of short glass-fiber reinforced nylon 6 (33 wt.%): Tensile strength and strain at yield vs. moisture at 23°C.

Changes in moisture content (from 0.2% to 1.2%) affect the decrease of the tensile strength and Young's modulus and increase of tensile strain at tensile strength (Figure 14). Moisture content increase from 1.2% to 1.75% is not so significantly affected to tensile properties of fiber-glass reinforced nylon 6 in comprizing with the range 0.2 – 1.2% (Figure 13 and 14). At this range of moisture content changes, the reduction of the tensile strength (for 33 wt.% GF) is 5-6% approximately. Tensile strains will increases by 15-20%. Taking into account, the combined temperature and moisture effects are very important for the assembled parts design on the stage of material pre-selection and initial finite element analysis (FEA). Prediction of the long-term cyclic performance of the assembled automotive components requires having comprehensive long-term properties of used thermoplastics and metals.

<u>The Influence of Reinforcements on Long-Term Mechanical Properties of Nylon 6</u>

The following long-term properties (at tensile, compressive or flexural loading conditions and at various end-use temperatures and initial stresses) of thermoplastics are important for assembled plastic parts design, design and assembly process analysis & optimization:

- Creep data (modulus, creep rupture strength, isochronous stress-strain creep curves)
- Stress relaxation

- Fatigue data ($S - N$ curves; fatigue cracks propagation data ($\Delta l / N$ or $\Delta l / \Delta K_1$); critical fracture toughness (K_{1C}) data).

Highly reinforced (GF ≥ 30 wt.%. and above) plastics have improved resistance to creep (Figure 15) and fatigue with the influence of various temperatures when compared with similar fiber-glass loaded grades of conventional nylon 6 [6, 11, 35-36, 40].

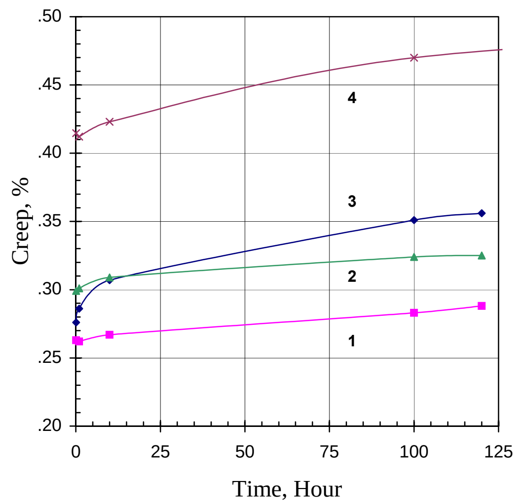

Figure 15. Influence of reinforcement type on resistance to tensile creep of nylon 6. Legend: material state: DAM, color - natural state; Test temperature - 23°C; 1 - 63 wt.% GF; 2 – 50 wt.% GF; 4 - long fiber-glass (50 wt.% GF); 4 – 33 wt.% GF.

<u>Kinetic of Coefficient Linear Thermal Expansion</u> α : <u>Key Factor of Integrated/Smart Behavior of Assembly</u>

In order to select right materials for assembled parts that will maintain acceptable end-use performance (at various temperatures and various environments), automotive product designer and technologist must be aware of the several design-end-use considerations. The following four concerns need to be taken into account, which correlated with thermal and dimensional properties of plastics:

1) Both the normal and extreme operating environments to which an assembly will be subject (under-the-hood, interior, exterior, etc.);
2) Duration of exploitation/end-use;
3) Part and mold-tool design;
4) Processing parameters of injection molding.

In general, an induced thermal stress in assembled plastic components is a result of the effects of low thermal diffusivity, high thermal expansion with temperature. Thermal expansion (at temperature *t,* for specific volume *v,* and length *L*) can be defined by the following three parameters:

1) Specific thermal expansivity (in cm^3/g °C), in which $e = (\partial \nu / \partial t)_P$.
2) Volume coefficient of thermal expansion of volume (in 1/°C), in which $\alpha_V = 1 / \nu (\partial \nu / \partial t)_P$.
3) Linear coefficient of thermal expansion (in 1/°C), in which $\alpha = 1 / L (\partial \nu / \partial t)_P$.

The linear coefficient of thermal expansion α of reinforced thermoplastics has been recognized as one of the important thermos-mechanical properties [10-11, 14-15, 35-36, 39-41] because thermal stability is regarded as a critical issue in many automotive applications (assembled thermoplastic components). Exposure to various environments (additional to temperature) such humidity (*RH%*), various chemicals, etc. may result in a change in the dimension of thermoplastic only part due to moisture/solvent absorption, stress relief and thermal expansion. Sizes of metallic screws will not be changed by influence of moisture/humidity only. Both factors (linear coefficient of thermal expansion α and moisture/humidity *RH* will effect on kinetic of tightening load Q_{VO}. Previously, we demonstrated the kinetic of Q_{VO} by temperature change ΔT (see equation 10). With the influence of the both factors (α, *RH*), the tightening load will be influenced by combined effect on ΔQ_Σ [14-15]:

$$\Delta Q_\Sigma = \Delta Q_{TEMP} + \Delta Q_{RH} \tag{17}$$

$$\Delta Q_\Sigma = \frac{l \Delta T \{ [(\alpha_{PL} + \frac{\varepsilon_{RH}}{\Delta T}) - \alpha_{SC}] \}}{(\lambda_{SC} + \lambda_{PL})} \tag{18}$$

Where:

ΔQ_Σ = Changes of tightening load Q_{VO}.

ΔQ_{RH} = Influence of moisture effects on tightening.

ε_{RH} = Linear dimensional changes of joined thermoplastic with influence of moisture/humidity.

Thermoplastics properties and processes are influenced by their thermal characteristics such as melt temperature (T_m), glass-transition temperature (T_g), dimensional stability, thermal conductivity, thermal diffusivity, heat capacity, decomposition and coefficient of linear thermal expansion (α). The coefficient of linear thermal expansion α is important and mostly useable parameter in the plastic parts design for assembly. This coefficient α is influenced by the type of plastic (matrix) and composition, particularly the glass-fiber content and its orientation.

Table 6 and Figure 7 contain data on the coefficient of the linear thermal expansion α of various materials (matrix and reinforcements). The data indicates that most reinforcements, such as fiberglass and carbon-glass, which are used for reinforcement of various thermoplastics, have much lover coefficient of thermal expansion than polymers and metals. In general, the value of coefficient of linear thermal expansion α may vary from 5 to 30 (10^{-6} /^{0}C) for different reinforcements {such E-glass (α =2.8), A-glass (α =8.5), aluminum flakes (α =20-30)}. Precise analysis of the induced thermal stresses σ_t directly depends on the accuracy of the coefficient of linear thermal expansion α. There is a lot in literature that addresses to the theoretical and experimental data on coefficient of linear thermal expansion α of various un-filled and reinforced thermoplastics [3, 8, 10-13, 16, 23-27, 35-39].

Several different theories may help in predicting the value of α with the influence of properties of matrix and used reinforcements. Among them, the three simples are most commonly used for the design with reinforced thermoplastics. By the rule of mixtures [(1)] [38], coefficient of linear thermal expansion α of reinforced plastic (composition) is equal to:

$$\alpha^{(1)}{}_{PL}(t) = [\alpha_m(t)V_m + \alpha_f(t)V_f] \qquad (19)$$

Where:
$\alpha_m(t)$ and $\alpha_f(t)$ are the coefficients of linear thermal expansion of matrix and reinforcement respectively at temperature *t*.

V_m and V_f are the fractional volumes of matrix and reinforcements respectively.

Modified rule of mixture [(2)], equation (20) is based on an empirical constant k, assuming that specific volume (kV_f) has the value of α intermediate between the reinforcements and matrix [39]. By this modification, coefficient of linear thermal expansion of plastic (composition) is equal to:

$$\alpha^{(2)}{}_{PL}(t) = [\alpha_m(t)V_m + \alpha_f(t)V_f] - \{kV_f[\alpha_m(t) - \alpha_f(t)]\} \qquad (20)$$

Value of $\alpha^{(1)}{}_{PL}(t)$ is larger of $\alpha^{(2)}{}_{PL}(t)$ by

$$\Delta\alpha = \{kV_f[\alpha_m(t) - \alpha_f(t)]\} = \{kV_f\alpha_m(t)[1 - \alpha_f(t)/\alpha_m(t)]\} \qquad (21)$$

The ratio α_f / α_m is equal (0.03-0.04) approximately (see Table 7) for engineered plastics and both glass- or carbon- based fiber reinforcements. It was recommended [39] to use value of k =0.24 for several thermosets resins.

Similar by the structure to (18)-(20) is Turner theory[(3)], which taking into account the weighing factor as a function of the volume fraction and bulk module of the reinforcements and matrix. By Turner's model linear thermal expansion of reinforced thermoplastic α_{PL} is equal to:

$$\alpha^{(3)}{}_{PL} = \frac{\alpha_m(t)V_m E_m + \alpha_f(t)V_f E_f}{V_m E_m + V_f E_f} \qquad (22)$$

Where:
E_m and E_f = Young Modulus of matrix (polymer) and reinforcements (fibers).

These three equations (19)-(20) and (22) don't take into account the influence of the fiber orientation in molded parts. Depending on the manufacturing technology, molding tool design, etc. the α_{PL} can be quite different in different directions (at flow, perpendicular to flow, or by angle). Previously, we discussed [40] possibility to predict the tensile strength σ_{PL} of injection molded fiberglass reinforced plastics with the influence of fiberglass orientation and flow directions. The similar approach may be made for the coefficient of thermal expansion α_{PL} of fiberglass reinforced plastic also:

$$\alpha_{PL}(t) = C_0^{-1}(t, RH)[\alpha_m(t)V_m + \alpha_f(t)V_f] - \{kV_f[\alpha_m(t) - \alpha_f(t)]\}^n \qquad (23)$$

Where:
$C_o(T, RH\%)$ - is the orientation factor with the influence of temperature *t* and moisture *(RH)* effects. Value of C_0 is in the following range (approximately):

$$1 \geq C_0(T, RH) \geq 0.3 \qquad (24)$$

The orientation parameter $C_o(T, RH)$ is equal to 1 for longitudinal (at flow direction) orientation. The orientation of any single fiber may be calculated from its elliptical profile by the following equation:

$$\cos(\vartheta) = \frac{d_{\min or}}{d_{major}} = \frac{4A_{ellipse}}{d_{major}}, \qquad (25)$$

where: ϑ - is the angle the fiber-glass axis makes with the melt-flow direction: $d_{\min or}$ - is the minor axis, $d_{\min or} = d_f$; d_{major} - is the ellipse major axis, and A - is the area of the ellipse. The $\cos(\vartheta)$ data is the important factor in calculation of the value of orientation factor/parameter $C_o(T, RH\%)$.

Some calculation details of $C_o(T, RH\%)$ with the influence of Weibull distribution are presented in [39]. The value of empirical constant n in equation (23) is at range $0.3 \le n \le 1$ and may be different for various reinforced thermoplastics. Figure 16 presents examples [11] of the effects of fiberglass reinforcement (from 0 to 40 wt/%) on the coefficient of linear thermal expansion α for several thermoplastics (nylon 66, PBT, and PC based) at room temperature conditions.

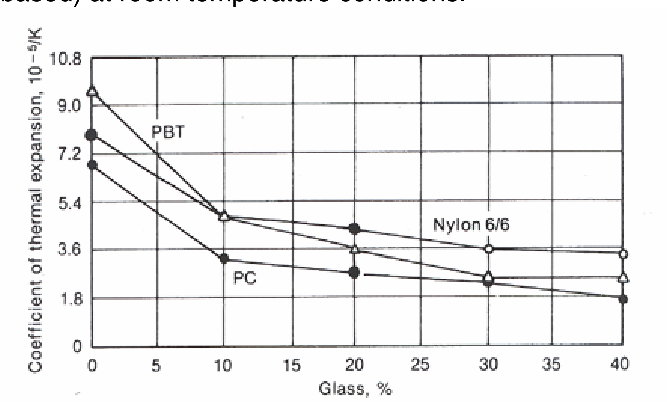

Figure 16. Influence of fiber-glass reinforcement on linear thermal expansion of three thermoplastics (nylon 66, PBT, and PC based, at 23°C, dry-as molded)

Table 12. Influence of fiber-glass reinforcement and fiber/flow orientation on the coefficient of thermal expansion α of nylon, 10^{-6}/ °K (at 23°C, dry-as-molded)

Type of Nylon GF wt.%	Nylon 6		Nylon 66	
	Flow	Cross	Flow	Cross
Un-filled				
(GF=0)	100	100	120	120
Fiber-glass Reinforced				
GF=15	38	120	-	-
GF=20	31	117	35	111
GF=25	23	112	33	112
GF=30	22	106	22	107
GF=35	20	104	20	100
GF=40	18	102	20	100
GF=45	16	100	20	100
GF=50	14	74	16	78
GF=63	12	78	14	78
Impact Modified (IM)				
IM=5	110	110	130	130
IM+30 GF wt.%	24	120	25	150

The value of α of glassy polymer is about half that of a liquid polymer. For crystalline polymers, the sharp increase in α occurs at the melting point T_m. Values of α for glassy and crystalline polymers are approximately equal. It has been mentioned above that end-use/test temperature *(t),* moisture *(RH)* and crystallininty may influent on value of α for nylon significantly Figures 16-17, Tables 12-14).

It is especially important if the temperature range includes a thermal transition such as glass-transition temperature T_g, which may vary in wide range with the influence of moisture conditions. Very significant are T_g changes at 100% RH, when T_g is switching to the area of minus temperatures. Figures 17 and Table 13 are providing an expended published data [35-36] on the influence of operating temperatures (from -40°C to 150°C) on α. The influence of fiberglass (flow) orientation on α is shown in Figure 17 and Table 12. Presented in Table 12, results for the cross-flow direction is showing very small dependence of α to the level of fiberglass reinforcement (at room temperature).

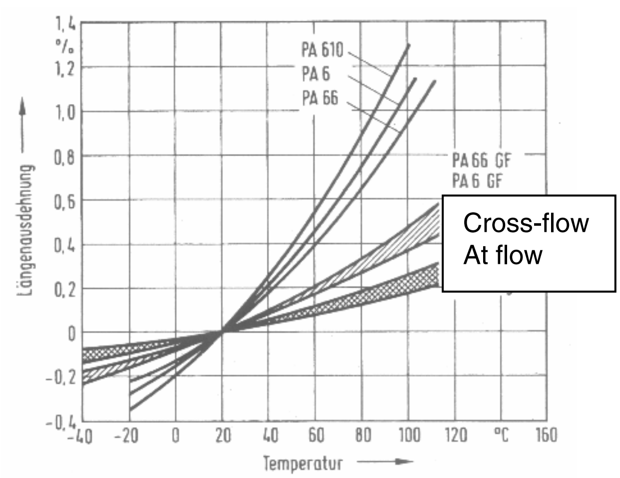

Figure 17. Influence of temperature on thermal expansion of the various nylons [36].

Table 13. Effects of temperature on the coefficient of linear thermal expansion α of nylon, 10^{-6} / ° K [35].

T (° C)	PA 6	PA 66	612	11
- 40		63	72	90
0		72	81	90
23	76-100	81-120	90-131	90-150
50				90
77		90	108	210
150				210

All these cross-flow results are closed to data developed for un-reinforced plastic at flow direction at 23°C. By [36], the value of α cross-flow is less than at the flow. Plastic flow orientation at fastening area depends on the design of part and molding tool. Some discrepancies in these experimental results for α may be explained by differences of used tests procedures, fiberglass orientation, moisture content and influence of molding conditions, which create differences in microstructure of plastics (level of crystallinity, etc.). Decrease in the crystallinity of nylon will increase thermal expansion of nylon by 28-35% approximately (Table 14).

Table 14. Influence of crystallinity on the coefficient of linear thermal expansion α of nylon, 10^{-5}/°C (at temperature range from 0 °C to 60 °C [36].

Nylon	Crystallinity (in %)	α = 10^{-6} / ° K
Nylon 6	15 - 35	100 - 66
Nylon 66	20 - 35	90 - 70

MECHANICAL PERFORMANCE OF ALUMINUM

The primary goal of this section is to provide some basic technical information, which will assist the design of plastic parts for assembly using aluminum made self-tapping screws. To do this, key short-term, long-term mechanical and tribological (coefficients of frictions) properties are discussed in detail. Aluminum is available in a number of product forms. The mechanical and tribological properties will depend on type of alloy, product form, manufacturing and assembly, and environment. Various aspects of the mechanical performance of aluminum alloys for fastening of components and structures are discussed in [11, 42-43].

Table 15. Typical Mechanical and Physical Properties (at 23°C) of Aluminum Alloys Used for Fasteners.

Type of Light Alloy	1100	2024	6063
Density, g/cm3	2.7	2.78	2.7
Composition	Al	Al, Cu, Mg	Al, Cu, Cr, Mg,
Tensile Strength, MPa *Annealed* *Strain-hardened*	 90 165	 185 485	 90 240
Young Modulus, GPa *Annealed* *Strain-hardened*	68.9	73.1	68.9
Elongation, % *Annealed* *Strain-hardened*	 45 17	 22 19	 18 12
Shear Strength, MPa *Annealed* *Strain-hardened*	 60 90	 125 280	 70 150
Thermal Expansion α , 10^{-6} / ° K	20	19	20

Short-Term Properties

Fastener materials may proactively be specified to beat meet the thermoplastic assembly application under various considerations and design criterion. The advantages of aluminum alloys for fastening of thermoplastics were presented in Tables 7-8. Aluminum alloys are used for fasteners where lightweight is an important assembly service criterion. The following three alloys are commonly manufactured into fasteners, with individual aluminum alloy selection dependent on strength requirements (Table 15). Typical stress-strain curve for aluminum alloy is shown in Figure 5. Some details of efficiency of aluminum by short-term properties criterion were presented in Tables 5-7. In stiffness- and weight-critical thermoplastic applications, aluminum made fasteners competes with steel and titanium alloys also.

Long-Term Properties

It was demonstrated previously in aerospace industry that aluminum alloys may deliver not only high strength and low structural weight, but higher long-term properties such as fracture toughness and corrosion resistance for high damage tolerance, durability and safety. By these reasons, aluminum is used in many automotive applications, where resistance to cyclic loading with time-temperature effects is very important.

Table 16 presents the influence of long-term aging effects (up to 10^4 hours) at typical end-use temperatures range (from -40°C to 150°C). This range is typical for under-the-hood automotive applications. At -40°C, tensile strength of aged specimens was changed very slightly (by 2-8% approximately). At elevated temperatures (from 100°C to 150°C), the tensile strength of aged aluminum decreased by 10-40% approximately.

Table 16. Influence of Time-Temperature Effects[9] on the Tensile Strength (in MPa) of Aluminum Alloys

Type of Light Alloy *Material State*	**Test Temperatures, °C** **-40**	 **23**	 **100**	 **150**
1100 - *Annealed* *Strain-hardened*	96.5 172	90 165	67 145	55 124
2024 - *Annealed* *Strain-hardened*	- 503	185 485	- 455	- 379
6063 - *Annealed* *Strain-hardened*	- 248	90 240	- 214	- 145

Table 17. Tensile Strength Influence on Fatigue Endurance[10] of Aluminum Alloys (at 23°C).

Type of Light Alloy	1100	2024	6063
Fatigue Endurance, MPa			
Annealed *Strain-hardened*	34 62	89.6 137	55.2 151
Endurance/Strength Ratio			
Annealed *Strain-hardened*	0.37 0.37	0.48 0.28	0.61 0.63

The influence of the temperature conditions on tensile strength of 33 wt.% glass-reinforced nylon was demonstrated in Figure 12; the creep data demonstrated

[9] These data represent the lowest tensile strength with the influence of time-temperature effects (after 10^4 hours of exposure at testing temperature under no load).
[10] Based on $5x10^8$ cycles of completely reversed stress.

in Figure 15. Tensile strength (the key parameter of short-term properties) of analyzed aluminum alloys reflects to resistance to cycling loading as parameter of long-term mechanical properties (Table 17).

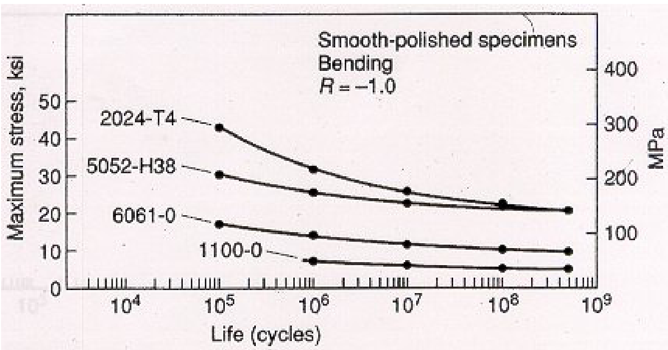

Figure 18. Flexural fatigue data: S-N curves for analyzed aluminum alloys (1100 – annealed; 2024 – strain-hardened; 6061/6063 - strain-hardened) at 23°C, symmetrical stress cycle *R*= -1.

The composition of these alloys and fabrication process contribute to the differences in the ratio of endurance/tensile strength from 0.28 to 0.63. A consistent trend in fatigue that varies with tensile properties of aluminum alloys is shown in Figure 18. Fatigue strength (stress amplitude at cyclic failure) at the shorter lives (number of cycles to failure at range 10^5 - 10^6 cycles) reflect the tensile strength of tested alloys, but those at the longer lives (number of cycles to failure at range 10^7 - 10^{69} cycles) do not (Figure 18). Fracture toughness (K_{IC} and K_{IIC}) and fatigue crack growth data ($K_{IC} - dl/dN$) for various aluminum alloys may be obtain from [42-43].

<u>Tribological Properties of Interacting Surfaces (Aluminum with Plastic): Coefficients of Friction</u>

Coefficient of friction μ_{FR} is very important parameter in the design of plastic parts for assembly (fastener technology) in determining of the following three key assembly parameters (values):

- Driving torque (T_{DR})
- Tightening torque (T_T)
- Stripping torque (T_{ST})

Value of tightening torque (T_T) may be calculated by equations (26):

$$T_T = Q_{VO}\left[\frac{d_2}{2}\frac{\left(\frac{P_{SC}}{\pi d_2}+\mu'\right)}{\left(1-\mu'\frac{P_{SC}}{\pi d_2}\right)} + \mu''\frac{(D^3-d_0^3)}{3(D^2-d_0^2)}\right] \quad (26)$$

Where:

μ = Coefficient of friction at interacting surfaces (metal and thermoplastic)

μ' = Coefficient of friction in thread

$$\mu' = \frac{\mu'_{FR}\ (metal - plastic)}{\cos\frac{\alpha}{2}} \quad (27)$$

μ'' = Coefficient of friction at interacting surfaces (head of metal screw and metallic/or thermoplastic part)

P_{SC} = Pith of screw

d_0 = Nominal diameter of the screw

d_2 = Nominal diameter of the surface contact/friction

D = Diameter of the head of screw

There are two coefficients of friction:

- Static
- Dynamic

The lower the coefficient of friction μ_{FR}, the easier the two interacting surfaces will slide over each other. Figure 19 shows the kinetic of torque (Nm) as function of tightening time (sec) for self-taping screw in fiber-glass reinforced nylon 6. The tightening torque directly corresponds to the clamp (pre-load) conditions, which are very important factor in the mechanical performance of an assembly. Tribological properties (μ_{FR}) of thermoplastics are different from those for metals; and plastics do not behave to the traditional laws of friction. For example, in plastics coefficient of friction μ_{FR} actually decreases as contact stress increases. From the other side, the static coefficient of friction of plastics is typically less than the dynamic coefficient of friction of the same of interacting surfaces (Table 18).

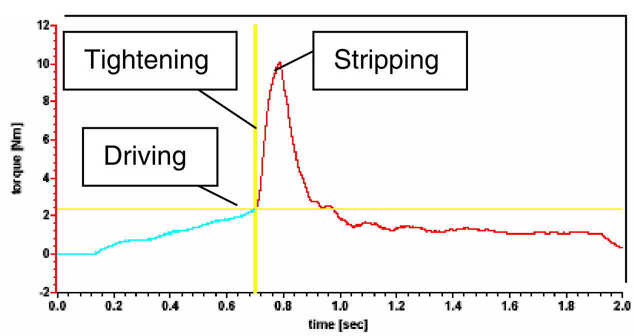

Figure 19. Relations between torque and tightening time (rotation of self-tapping screw).

Polyamide/nylon 6 is an ideal polymeric material for injection molded parts subject to sliding friction of interacting surfaces. Nylon 6 has proved to be superior to aluminum in withstanding erosion of this nature. An important feature of nylon is tribological performance in the absence of a special additives and lubricants. However, initial or continuos lubrication of interacting surfaces extends the range of design applicability for friction.

The key factors, that influent on the coefficients of friction μ_{FR} of interacting surfaces are:

- Materials composition of mated parts/surfaces (Tables 18-19)
- Roughness (Table 20)
- Velocity of sliding
- Contact pressure (Table 21)
- Design and finish of interacting surfaces (Table 19)
- Nature of intermediate medium in interacting surfaces
- Environment and temperature

Table 18. The influence of contact conditions on coefficient of friction μ_{FR} (nylon against steel)

Type of Nylon	Coefficient of friction μ_{FR}	
	Static	**Dynamic**
Un-filled plastics against steel		
Nylon 6	0.22	0.26
Nylon 66	0.20	0.28
Reinforced plastics against steel		
Nylon 6, 14 wt.% GF	0.24	0.28
Nylon 66, 15 wt.% GF	0.24	0.29
Nylon 6, 33 wt.% GF	0.25	0.31
Nylon 66, 33 wt.% GF	0.25	0.31

Table 19. The influence of contact conditions on coefficient of friction μ_{FR}.

Type of Nylon	Plastic	Steel	Aluminum
Nylon 66	0.20	0.20	0.10
Nylon 66, 33 wt.% GF	0.23	0.31	0.12

Table 20. The influence of surface conditions (depth of roughness) on coefficient of friction μ_{FR} (nylon against nylon/film to film. Average surface/contact pressure 0.1 MPa, surface temperature < 40°C).

Average of depth of roughness R_z (in μm)	Coefficient of friction μ_{FR}	
	Nylon 6	**Nylon 66**
0.1	0.35	0.5
0.5	0.33	0.43
1.0	0.32	0.38
2.0	0.32	0.35
4.0	0.36	0.38
6.0	0.46	0.46

The direct influence of reinforcements and fillers on coefficient of friction μ_{FR} only becomes important when the filler is at the contact surface. Injection molded surfaces are normally resin-rich, so the differential contraction between the reinforcement just below the surface at the matrix can cause a degree of irregularity in surface smoothness (Table 22). At reinforcement, concentration sufficiently high to reduce shrinkage on cooling polymerization, surfaces will be more nearly flat and thus reduce the plowing component of friction, which results from surface waiving.

Table 21. The influence of surface/contact pressure conditions on coefficient of friction μ_{FR} (nylon against nylon/film to film. At optimal depth of roughness R_z=1.5-3.0 μm, surface temperature < 40°C)

Average contact pressure (in MPa)	Coefficient of friction μ_{FR}	
	Nylon 6	**Nylon 66**
0.02	0.40	0.40
0.05 – 0.1	0.35 - 0.36	0.35 - 0.36
0.15	0.38	0.38
1.0	0.43	0.44
5.0 - 15.0	0.48	0.50 – 0.51

Fillers reduce the coefficient of friction μ_{FR} if they are fine enough to effectively increase the glass-transition temperature (T_g) of the matrix near the contact surface, since frictional heating and matrix softening are frequently responsible for high coefficient of friction μ_{FR}.

MECHANICAL PERFORMANCE OF INTEGRATED SYSTEM: REINFORCED NYLON 6 FASTENED BY ALUMINUM SCREWS

Below we will present a short overview on the efficiency of aluminum made self-tapping screws for fastening of fiber-glass reinforced nylon 6[11]. Developed test program includes evaluation of various design and assembly technology effects, such as:

- Conditions of the thread engagement by the
  - number of threads, or length
  - hole (internal) diameter of the bosses
- Influence of deformation properties of used metallic materials on kinetic of the load distribution at engagement area.
- Influence of thermos-mechanical properties of used metallic materials on clamp load/stress relaxation at wide range of end-use temperatures (from -40°C to 130°C).
- Influence of joint design version on mechanical performance under various end-use cyclic loading conditions.
- Kinetic of failure modes with design/material version.

This short review is not intended to be comprehensive, because our focus is on exploiting the exceptional

[11] These results are very important for advanced design of various under-the-hood plastic components such as air intake manifolds (AIM's).

mechanical performance of analyzed "reinforced nylon-aluminum assembly", toward the optimized design and correct industrial (automotive, transportation, etc.) applications.

MATERIALS, SPECIMENS AND TEST PROCEDURES

The following self-tapping fasteners and thermoplastics commercially available for various industrial applications, were used in this study:

- Injection molded short fiber-glass reinforced nylon 6 plastic (30 - 33 wt.% GF).
- Metallic (steel and aluminum made) self-tapping fasteners (Delta 60 - PT type).

Shapes of used bosses and fasteners are shown in Figure 19. Various short-term and long-term mechanical properties of aluminum were discussed above and presented in Tables 15-17. Tribological properties of nylon – fastener assembly discussed in Tables 18-21, chemical content of used alloys is presented in Table 22.

Table 22. Chemical properties of aluminum alloy

Component	Cu	Mg	Zn
Content, wt.%	1.2-2.0	2.1-2.9	5.1-6.1

Length of used self-tapping screws (metallic and aluminum) and bosses allowed varied the number of the threads in engagement from 4 to 8 threads (Figure 19). For design conditions, an engagement length will vary from 9.2 mm to 17.4 mm.

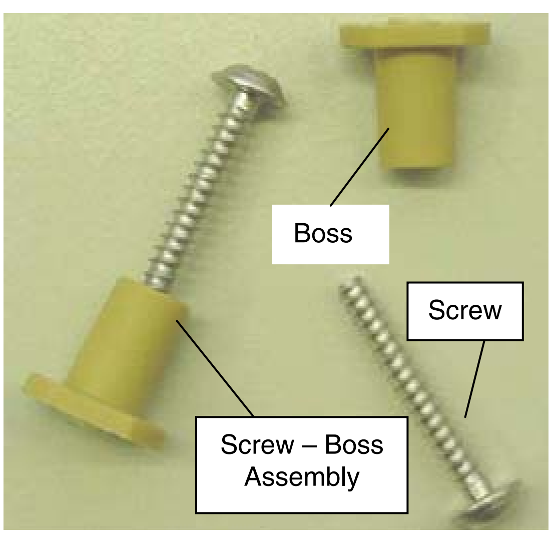

Figure 19. Test modes/specimens (an injection molded boss and self-tapping screw – Delta 60).

MECHANICAL PERFORMANCE DATA

<u>Assembly Considerations (Drive/Installation and Fail Torque)</u>

One of the most important problems of self-tapping screws in steels, light alloys and plastics is stripping (fail) during assembly. The PT type screws were designed for use in thermoplastics provide optimized fail/drive (installation) ratio. Figure 20 shows typical ratio for installation (T_i) and strip torque values (T_s). Due to differences in coefficients of friction μ_{FR} (see Table 19). The installation of aluminum self-tapping screws in reinforced nylon 6 require less energy (torque moment) than steel made at wide range of engagement (from 4 to 8 threads). Assembly with aluminum self-tapping fasteners can carry larger ultimate (strip) torque value when a number of engaged threads are equal to 6 or above (Attachment 1).

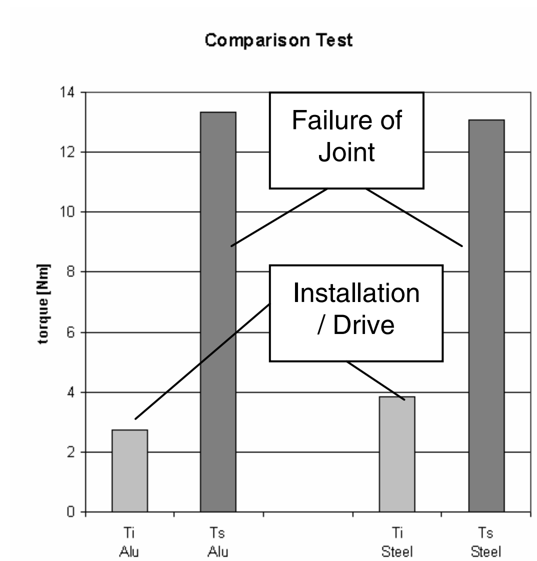

Figure 20. Influence of used fasteners on installation and ultimate conditions of assembly (Delta 60, number of engaged threads = 4).

Attachment 2 shows retention of installation (drive) torque after one-five repeated assembly/disassembly cycles. Due to differences in coefficients of friction μ_{FR}, the installation of aluminum self-tapping screws in reinforced nylon 6 require less energy (torque moment) than steel made at wide range of engagement (from 4 to 8).

<u>Resistance to Tensile Loading (Pull-Out Strength)</u>

Attachment 3 shows the influence of engagement length on tensile (pull-out) strength of joints. The values of pull-out strength increase with the influence of engaged threads (from 4 to 6). Further increase from 6 to 8 (or from 13.7 mm to 17.4 mm) will not influent on the pull-out performance. Due to the differences in stiffness between steel an aluminum (E_i / E_{AL} = 0.143, see Table 7) aluminum made screws perform equally to steel made at optimized engagement length conditions (n = 6 threads).

Resistance to Cyclic and Dynamic Loading

The following types of dynamic loads are typical for assembled/fastened parts:

- impact
- alternating (cycling) resulting in
  - possible fatigue damage (or failure)
  - vibration (possible clamp loosening)
  - thermal (or thermal combined with mechanical loads/stresses)

By the duration and shape the dynamic loads may be classified by the following way:

- sinuosoiduly (alternatives) typical for automotive applications, rotating parts
- short duration peak loading

Due to differences in coefficient of linear thermal expansion α between steel and aluminum (for details see Tables 6-7), the assembly with aluminum made fasteners are providing sufficient residual clamp conditions than steel made fasteners (Figure 21-22).

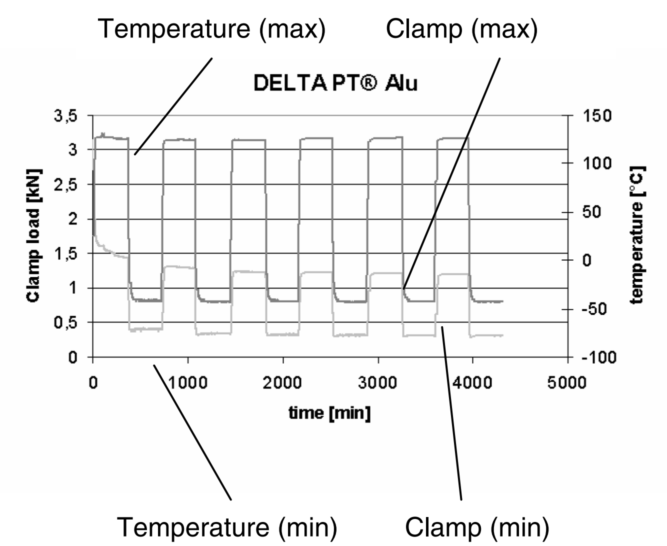

Figure 21. Influence of time-temperature effects on the kinetic of clamp load for aluminum made fastener.

MASS EFFECTS

The fastening characteristics, such as screw and joint geometry, and the materials characteristics, _such as density_, play a very important role in the response of joined self-tapping assemblies to cyclic and dynamic (vibration) loading. For the threaded joints, there are two important aspects to the nature of mechanical response:

- Damping characteristics of used material(s)
- Geometry of the joint and self-taping screw

As the results of dampening, a part of the energy from cyclic (dynamic) loads is absorbed and its effect dissipated. If joined and screw materials have high-energy –absorbing characteristics, more vibration energy in the form of changing dynamic load carrying may be benefit from a self-tapping fastener assembly. The density mass effects of screw(s) material are the *inertia* of those materials. From this perspective, aluminum made screw will keep residual clamp load more efficiently under various vibrations.

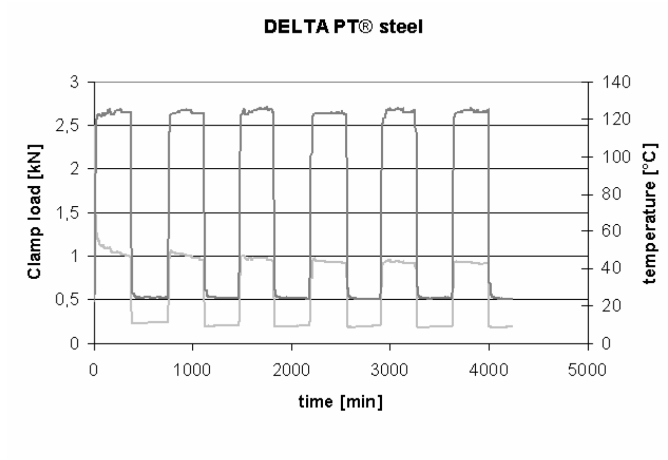

Figure 22. Influence of time-temperature effects on the kinetic of clamp load for steel made fastener.

Figure 23 provides kinetic of clamp load with the influence of time temperature conditions (maximum temperature is 120°C).

Figure 23. Kinetic of clamp load under cyclic loading with influence of temperature (stress ratio = 0.3).

CONCLUDING REMARKS

Today's focus is on advanced engineering materials and joining (fastening) that can help achieve low-cost manufacturing without sacrificing mechanical performance. Utilization of traditional mechanical performance parameters and fracture mechanics criteria, allows more efficient selection of materials for mechanical fastening of thermoplastics. With respect to mechanical, thermal and fracture toughness properties, aluminum alloys are closer to reinforced thermoplastics (such as nylon/polyamides, PBT, PET, etc.) than steels when used as fasteners.

Joining reinforced thermoplastics with self-tapping aluminum screws makes it possible to create integral/smart structures. Improved interaction between aluminum fastener and reinforced thermoplastic provides increased mechanical performance of assembled components under various end-use conditions.

The proposed replacement of fastener material (from steel to aluminum) will allow management of stiffness issues, short-term (strength) and long-term (life) performance of assembled plastic parts in various automotive applications. Aluminum fasteners were produced without significant changes in the design, geometry, processing and assembly technology.

The production and future re-design of fasteners is considered to be satisfactory. Manufacturing costs for aluminum fasteners may decrease in the future due to mass production, especially when integral assembled products are optimized during the design and manufacturing process. Results from this investigation provide recommendations on material pre-selection for the design of fastened thermoplastic components with improved mechanical performance.

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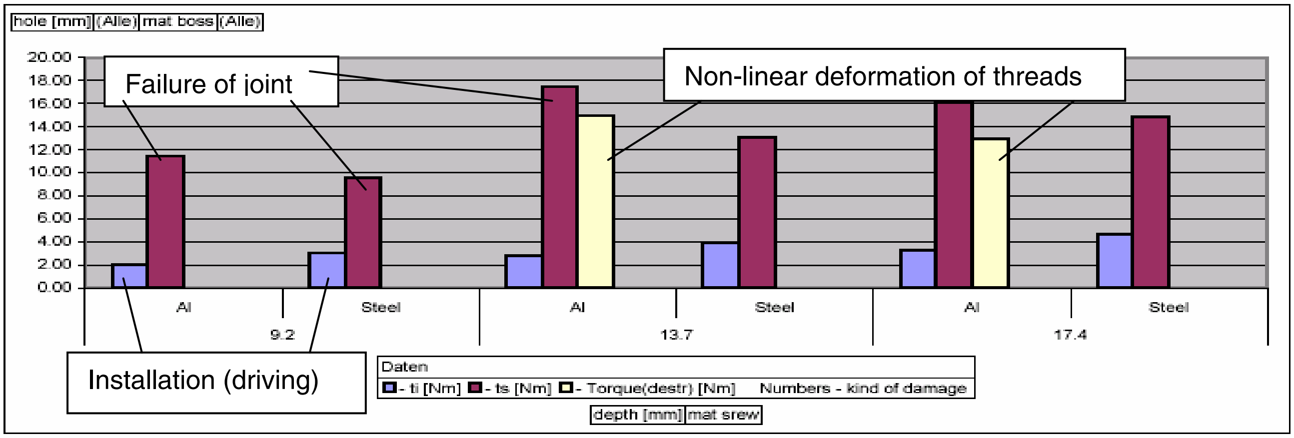
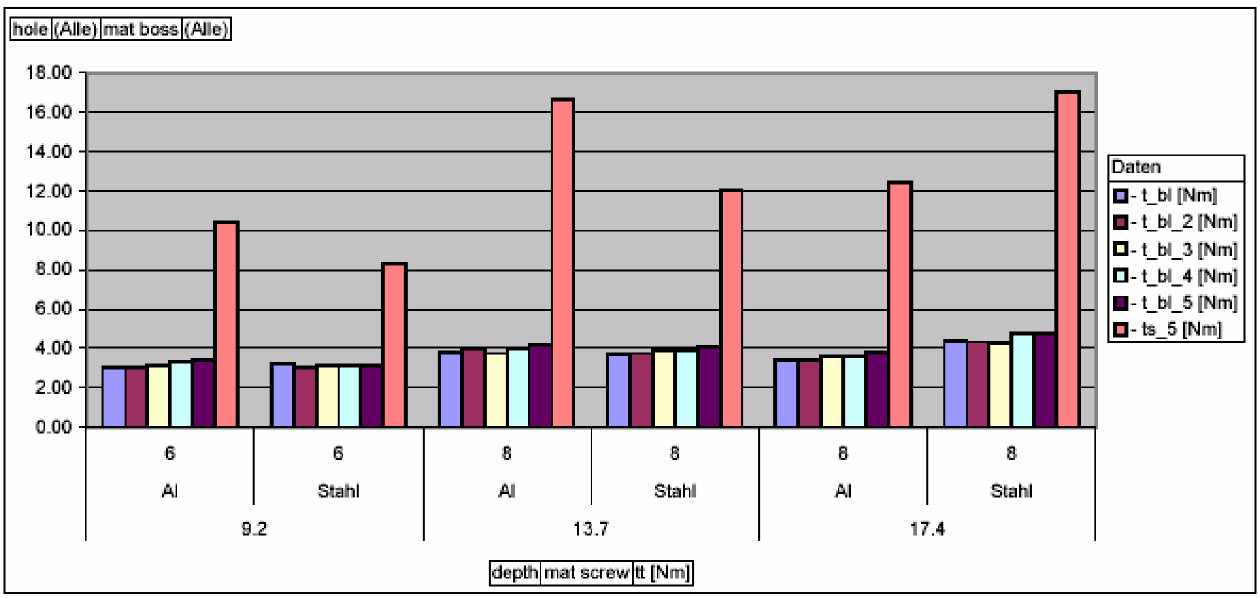
KEYWORDS

Polyamide, nylon, thermoplastic, screw, self-tapping; self-cutting, mechanical performance, strength, strains, fatigue, thread, boss, nut, bolt.

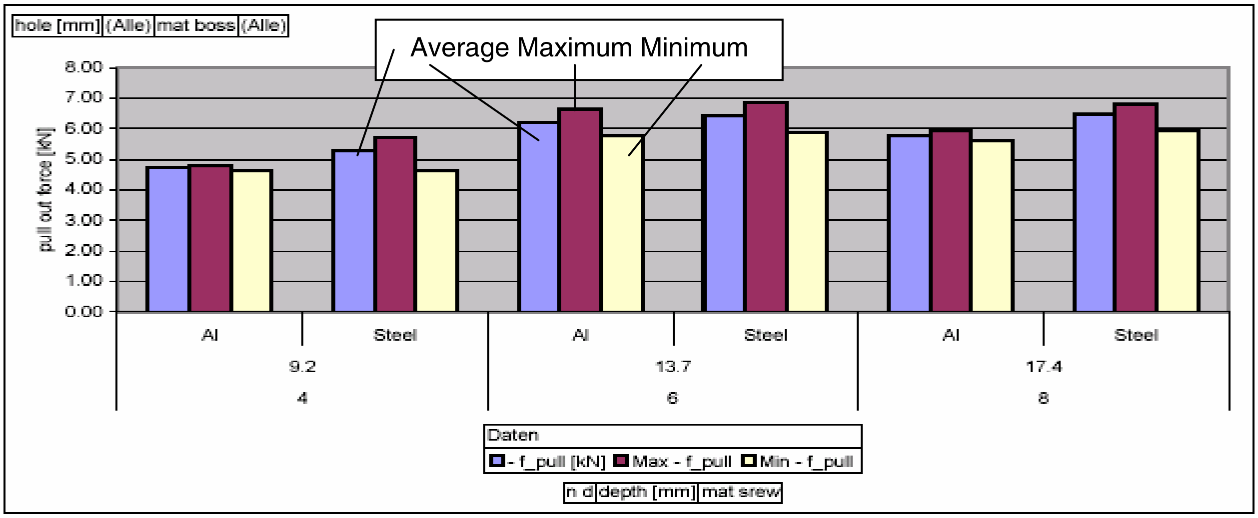
Attachment 1. The Influence of engagement length on assembly considerations (drive/installation and fail torque) at 23°C.



Attachment 2. The Influence of engagement length on assembly considerations (retention of drive/installation) at 23°C.



Attachment 3. The Influence of engagement length on the resistance to tensile (axial) loading at 23°C.



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